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Microclimate Studies in Uniform Shelterwood Systems in the Sub-Boreal Spruce Zone of Central British Columbia

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Robert M. Sagar and Michaela J. Waterhouse

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ABSTRACT

In the Sub-Boreal Spruce dry warm (SBSdw) biogeoclimatic subzone, on the Interior Plateau of British Columbia, frost is a limiting factor for the establishment and growth of Douglas-fir (*Pseudotsuga menziesii*). A research trial, using a uniform shelterwood silvicultural system, was harvested in 1991, then again in 2001, to test how residual basal area retention affected regeneration establishment, growth, and condition. Microclimate stations were installed in two of the residual basal area treatments (15 m^2/ha and 20 m^2/ha) to measure frost events. From 2001 to 2008, near-ground air and soil temperatures were monitored on two pairs of adjacent 20 m^2/ha and 15 m^2/ha treatments along with one additional replicate of the 20 m^2/ha treatment, and a clearcut.

Minimum air temperatures and total duration (minutes) of air temperatures below 0°C were compared between treatments during the bud flush (15 May–31 July) and bud set (15 August–30 September) seasons. The clearcut treatment had a much longer duration of subfreezing minutes than the forested treatments for both bud flush and bud set periods, as well as a greater number of frosts and lower extreme minimum temperatures. Differences between the 15 and 20 m^2/ha treatments were not as great; however, both 15 m^2/ha treatments had longer duration of subfreezing minutes and increased numbers of frosts compared to the 20 m^2/ha treatments. The sky view factor increased as basal area decreased, and was positively correlated with the duration of subfreezing minutes. There were few significant frost events during the June to mid-August period in the forested treatments over the 7-year study. The data suggest that residual basal areas of 15 m^2/ha or greater provide adequate frost protection for regeneration.

ACKNOWLEDGEMENTS

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1 INTRODUCTION

Growing season frost has been identified as a serious problem for establishment of forests following clearcut harvesting in some biogeoclimatic subzones within the Interior of British Columbia (B.C.) (Stathers 1989; Steen et al. 1990). In the dry, warm Sub-Boreal Spruce subzone (SBSdw) in central British Columbia, poor performance of Douglas-fir (*Pseudotsuga menziesii*) due to frost damage in clearcuts has led to the conversion of prime Douglas-fir dominated forest to lodgepole pine (*Pinus contorta*). This is a forest management concern because Douglas-fir has high biological and timber value. To address the issue of conversion, a research trial was established in the SBSdw, in 1990, to test shelterwood silvicultural systems to perpetuate Douglas-fir dominated forests (Burton et al. 2000).

Stathers (1989) and Hungerford and Babbitt (1987) both suggested that shelterwoods could limit the exposure of young seedlings to growing season frost damage. The residual overstorey canopy should increase the minimum air temperature and reduce the incidence of severe frost. Temperatures below −4°C in June caused an irreversible decrease in photosynthesis in Engelmann spruce (*Picea engelmannii*) (Delucia and Smith 1987) and similarly in August for Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) (Lundmark and Hallgren 1987).

Chen et al. (1993) made microclimate measurements along a continuum from clearcut to edge to the old-growth environment. They showed that diurnal ranges of solar radiation, soil temperature, air temperature, and wind speed were reduced in the forested environment. Man and Lieffers (1997) demonstrated that partial cut treatments protected spruce seedlings and improved their productivity. They observed relatively greater depression of spring and fall photosynthesis for trees grown in the open compared to those grown under limited light yet protected from cold events by a partial overstorey. Blennow (1998) showed that nighttime minimum air temperatures increased by as much as 4.6°C in a shelterwood (275 stems per hectare or about 75% of basal area retained) over those measured in a nearby clearcut. Correspondingly, increased basal area retention has been shown to decrease frost damage in Norway spruce seedlings (Langvall and Orlander 2001). The authors found that frost injury was minimal at basal areas above about 25 m^2/ha and began increasing at lower basal areas. Similarly, Sagar et al. (2005) found that the number of frost events were substantially lower in irregular group shelterwood treatments as compared to clearcuts in the west Chilcotin area of central British Columbia. This reduction in frost events corresponded to improved survival and growth of interior spruce (*Picea glauca* × *Picea engelmannii*) (Daintith et al. 2005).

The increase of minimum air temperatures is not the only mechanism by which an overstorey canopy can reduce frost damage. Dang et al. (1992) found that the combination of a hard frost followed by exposure to high levels of direct solar irradiance is especially damaging to seedlings; conversely, shading after the frost enhances recovery by limiting excess trapped light energy within the needles. Langvall and Lofvenius (2002) showed that increased stem density in a shelterwood system delayed budburst by up to two weeks in Norway spruce seedlings, thereby allowing seedlings to avoid severe early season frosts.

Tree canopies can increase minimum air temperature through a reduction in the loss of longwave radiation at the forest floor (Holbo and Childs 1987). Tree boles and canopies generally have a much warmer radiative temperature than the sky (especially a clear sky); therefore, increasing canopy cover decreases the loss of longwave radiation to the sky by objects such as tree seedlings. This warms seedling temperatures and decreases the length and severity of frosts. Aerodynamic mixing of warmer air down to the surface caused by the interaction of wind with tree canopies (Granberg et al. 1993) is another mechanism that reduces frost occurrence.

The effect of canopy cover on surface objects can be quantified in terms of sky view factor (S_{vf}) or its inverse, canopy view factor (C_{vf}). A number of studies have shown that sky view factor is correlated with nighttime minimum air temperatures (Groot and Carlson 1996; Blennow 1998). Pritchard and Comeau (2004) showed that frost duration was negatively correlated to canopy height and density surrounding small openings in young aspen stands.

This study was initiated in 2001 as part of a uniform shelterwood trial located in the SBSdw near Williams Lake, B.C. (Burton et al. 2000), after a second harvesting entry was completed. The focus of the main trial was to test various levels of residual basal retention and harvesting methods on the establishment, survival, and productivity of Douglas-fir regeneration. The microclimate component was set up to help interpret tree performance by comparing the climate conditions among three of the residual basal area treatments (0, 15, and 20 m^2/ha).

The objectives for the microclimate portion of the shelterwood project were:

1. to compare soil temperatures and snow-free periods among the three residual basal area treatments (0, 15, and 20 m^2/ha);
2. to compare the incidence, duration, and severity of growing season frosts among the three residual basal area treatments (0, 15, and 20 m^2/ha); and
3. to investigate the effects of local canopy density on minimum near-ground air temperatures and duration of frost events during the growing season.

2 METHODS

2.1 Study Area

The three replicated study sites are located in the Central Cariboo Forest District north to northeast of Williams Lake, B.C., on the Interior Plateau (Figure 1). The Gavin Lake Road (GLR) and Alex Fraser Research Forest (UBC) sites are near Gavin Lake within 2 km of one another (52°28′; 121°47′), while the Beedy Creek (BEE) site is about 25 km to the northwest (52°38′; 122°06′) of the Gavin Lake Road sites. Mean site elevations are 820 m for BEE, 1000 m for GLR, and 980 m for UBC; the aspects are warm (135–270°); and slopes are gentle (0–20%) (Table 1).

These sites are in the Sub-Boreal Spruce dry warm biogeoclimatic subzone, Horsefly variant (SBSdw1) (Steen and Coupé 1997). The dominant site series is zonal (01 SxwFd – Pinegrass), and the soil type is a moderately well-drained Luvisol with a mor humus form (Burton et al. 2000).

The original stands, in 1990, were a mix of mature (118–138 years old) Douglas-fir (65–83% by volume), followed by lodgepole pine, interior spruce, subalpine fir (*Abies lasiocarpa*), birch (*Betula papyrifera*), and aspen (*Populus*

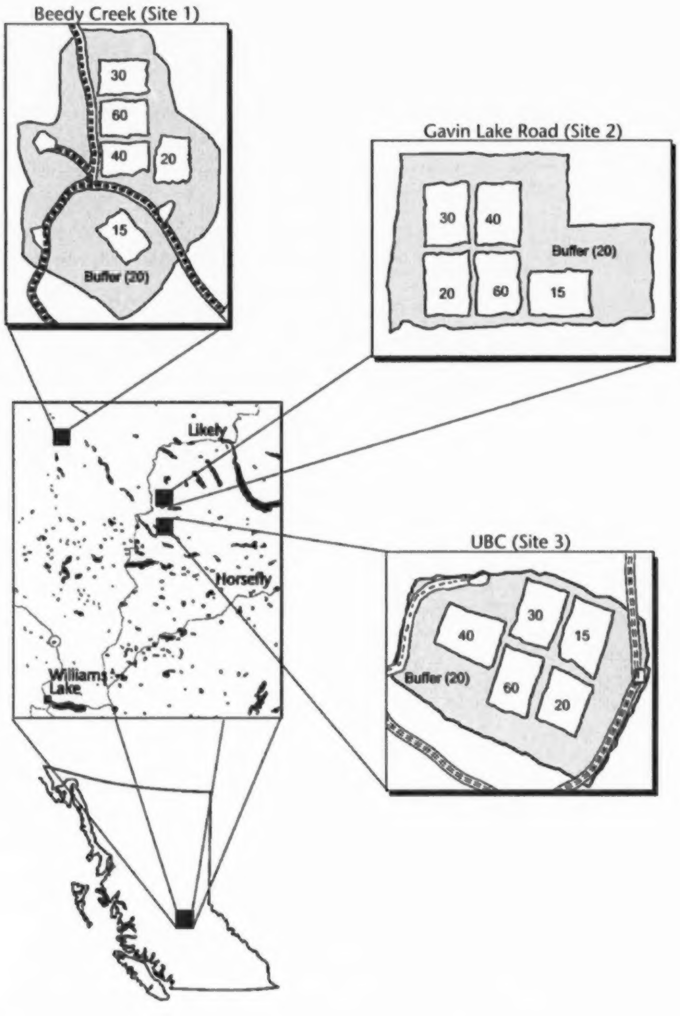


FIGURE 1 *Location of study sites and treatment units within each site.*

TABLE 1 *Site and stand description for each treatment unit (TU): elevation, slope, aspect, number of sample trees, height, diameter, gross basal area, and gross volume for trees >7.4 cm diameter at 1.3 m above ground in 2001*

Site[a]	TU	Elev. (m)	Slope (%)	Aspect (°)	Sample trees (n)	Height (m) mean±std	Diameter (cm) mean±std	Basal area (m^2/ha)	Volume (m^2/ha)
BEE	20 m^2	820	0–20	270	64	37.2±3.5	47.8±10.0	18.7	227
GLR	20 m^2	1000	4–15	225	79	36.0±1.7	51.9±8.4	21.1	244
UBC[b]	20 m^2	980	0–5	flat	75	33.2±2.2	45.8±6.4	19.7	234
BEE	15 m^2	820	0–20	270	53	38.2±5.1	51.0±13.9	14.2	179
GLR	15 m^2	990	4–15	135	65	32.4±3.4	37.2±10.7	17.3	189
GLR	0 m^2	1020	4–15	270		–	–	–	–

a BEE: Beedy Creek; GLR: Gavin Lake Road; UBC: Alex Fraser Research Forest.
b In 2007, basal area was measured at 12 m^2/ha.

tremuloides) (Burton et al. 2000). The mean pre-harvest basal area was approximately 61 m^2/ha across the three sites. The 2001 height, diameter, basal area, and volume for trees over 7.4 cm at 1.3 m above ground are summarized in Table 1. By 2007, the basal area was reduced to 12 m^2/ha in the UBC 20 m^2/ha treatment unit due to treefall.

2.2 Experimental Design

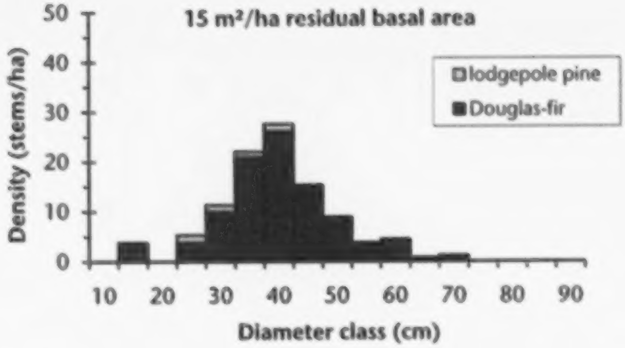
2.2.1 Silviculture The study design is a randomized complete block consisting of five 1.4-ha treatment units at each of three sites. The overall size of each study site ranged from 20 to 40 ha, with the treatment units being separated by 20-m buffer strips and up to a 100-m buffer outside of all treatment units.

The first harvest on the sites took place in 1991. The five treatment units were designed to compare the effects of residual basal area retention (60, 40, and 30 m^2/ha), and method of harvesting (fellerbuncher vs. handfalling) (Burton et al. 2000). The buffer area around the treatment units was also thinned to 40 m^2/ha using a fellerbuncher. In 2001, the 40 m^2/ha and 30 m^2/ha treatments originally made by the fellerbuncher in 1991 were thinned a second time, again with a fellerbuncher. In the 40 m^2/ha treatment units and buffers, the basal area was reduced to about 20 m^2/ha, while the 30 m^2/ha treatment units were thinned to about 15 m^2/ha. The intention of the second harvest entry was to improve the condition and growth of the established regeneration by reducing overstorey competition for light, moisture, and nutrients, but retaining a measure of frost protection.

The treatment units were thinned from below, preferentially removing lodgepole pine, interior spruce, subalpine fir, and deciduous trees, then the smaller diameter classes of Douglas-fir. The same thinning from below guidance was used when trees were marked-to-leave for the 2001 harvest. The large diameter Douglas-fir trees of good form were left evenly distributed across the treatment units and buffer areas to maintain frost protection. On average, there were 130 stems per hectare (86% Douglas-fir) left in the 20 m^2/ha unit and 105 stems per hectare (94% Douglas-fir) remaining in the 15 m^2/ha unit. The distributions of stems by size class in the residual stands are shown in Figure 2. The final cut on all treatment units is scheduled for 2010.

2.2.2 Microclimate Five microclimate monitoring stations were installed in five treatment units during the summer of 2001. A sixth station was added to the experiment in June 2005 to provide another replicate. The six climate stations were named according to research site (GLR, UBC, or BEE) and treatment unit residual basal area (20 m^2/ha or 15 m^2/ha, hereafter labelled 20 m^2 and 15 m^2). Two of the stations were within the GLR site (GLR 20 m^2 and GLR 15 m^2). The clearcut treatment was located on the north boundary of the GLR site and is called GLR 0 m^2. A fourth station was located in the Alex Fraser Research Forest (UBC 20 m^2). At Beedy Creek, the installations were called BEE 20 m^2 and BEE 15 m^2 (installed in 2005).

The topography near the microclimate stations in the GLR block is a gently sloping bench, located mid-slope above the valley bottom. The GLR 0 m^2 location is north of the block, at a slightly higher elevation, on a plateau with depressions and mounds (2- to 3-m relief). The BEE 20 m^2 location is flat to a lower slope position, while the BEE 15 m^2 station is on a gentle slope facing southwest and in a lower slope position. The UBC site is flat. These site characteristics are summarized in Table 1.



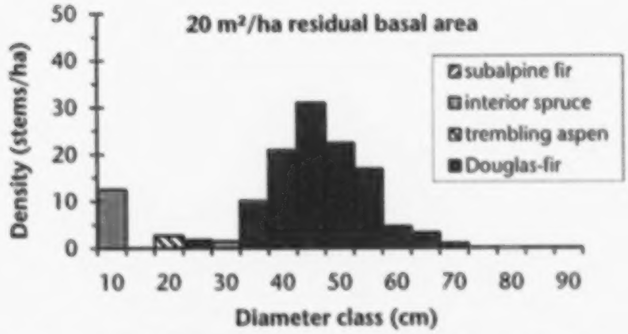


FIGURE 2 *Stem density by size class and species in the 15 and 20 m^2/ha residual basal area treatments (values represent averages for all replicate plots combined by treatment).*

Nine measurement locations were chosen at each microclimate station (except six at GLR 0 m^2) for air temperature and two for soil temperature. Sample points (posts) on the forested treatments were located on two or three transects, starting from near a tree bole (1 m) and extending to canopy gap centres (10–16 m). The actual distance from the tree bole for each measurement post is given in Appendices 6 and 7. The canopy gap centre was visually estimated. Soil temperature measurement locations in the forested sites were located beneath overstorey canopy (1–5 m from the tree bole) and near gap centre (10–16 m). At the clearcut site (GLR 0 m^2), two of the six air temperature measurement locations were in positions judged to be of average slope, two in depressions, and two in shedding locations (slopes of mounds). One soil temperature measurement location was at an average slope position and one in a depression.

In the BEE 15 m^2 treatment, there was more large (1–3 m tall) advanced regeneration than in the BEE 20 m^2 treatment. To mitigate concern that the presence of large advanced regeneration near the sensor locations would confound the results, some of the advanced regeneration within 5 m of the sensor locations at BEE 15 m^2 was removed in mid-May 2006.

2.3 Micro-meteorological Instrumentation and Data Collection

Air temperature sensors were unshielded, 30 AWG Chromel-Constantan (Omega Engineering Inc., Laval, Que.) fine wire thermocouples, constructed by twisting and soldering the wire, giving an effective diameter of 0.5 mm for the junction. These sensors were mounted on wooden stakes, 15 cm above the ground. Reference temperatures for the thermocouple measurements were measured with thermistors (YSI Inc., Yellow Springs, Ohio, Model 44002A) mounted on the datalogger wiring panel. Soil temperature sensors consist of thermistor beads potted in conical or cylindrical pieces of epoxy. Due to progressive failure of some of the soil temperature thermistors, all sensors were replaced in May 2005 with twisted and soldered thermocouples (24 AWG Chromel-Constantan) placed in a 3-cm long piece of 6.4 mm (¼ inch) brass tubing and encased in epoxy resin. Sensors were buried 10 cm beneath the air/organic layer interface.

Data were collected using CR10X dataloggers and SM192 storage modules (Campbell Scientific Canada Corp., Edmonton, Alta.). The dataloggers took readings of all sensors once per minute. Daily maximum, minimum, and average values were recorded for all sensors. Hourly averages of air temperature were recorded. Frost duration (Σt_0), which was defined as the total number of minutes (summer) and 10-minute periods (winter) when air temperature was less than 0°C, was recorded daily for each sensor.

2.4 Hemispherical Canopy Photography

Photographs of the overhead canopy at each air temperature measurement post were taken with a Nikon Coolpix 900 digital camera with a fish eye lens. The camera lens was positioned directly over the post at a height of 1.3 m above the ground. The camera was levelled with a single bubble level on the tripod and the camera was aligned south using a hand held compass. Pictures were taken at four forested treatments during the summer of 2001 and repeated for all treatments during the summer of 2006. Sky conditions were variable, ranging from overcast to sunny during the picture taking. A sun shade was employed to limit glare in cases where there was direct sunlight falling on the photo point. During subsequent processing of the pictures, the area covered by the sunshade was digitally changed to white pixels (canopy gaps).

Canopy density was calculated using methods described in Teti (2008). Analysis of each picture yielded canopy densities (C_d) in 10° increments from 0 to 90° (e.g., 0–10°, 0–20°), where 0° is the zenith and 90° is ground level. Canopy density represents the fraction of the total picture area in each increment class occupied by canopy and boles.

Hemispherical photography has been used to make quantitative estimates of the sky view factor at a point beneath the forest canopy (Blennow 1995, 1998). The sky view factor can be determined from a hemispherical photo by summing up the gap fractions ($1-C_d$) (weighted by the cosine of zenith angle) within each incremental area over the entire hemisphere.

Sky view factor is an index of the relative effectiveness of longwave radiation transfer from a given point in space to the surrounding hemisphere of sky. In this study, sky view factor was measured at the camera lens focal points and can be thought of as representing the effectiveness of longwave radiative transfer from a seedling. A sky view factor of 1 would indicate that there is no canopy visible in the hemispherical photo, while a sky view factor of 0 indicates that the sky is completely obscured. A point on the ground with a high sky view factor cools more rapidly than a point with low sky view factor and therefore has a greater likelihood of cooling to the freezing point.

2.5 Data Analysis

Snow cessation dates were determined by examining the diurnal temperature range as measured by the 15 cm air temperatures at each post. Snow-covered sensors have a small diurnal temperature range with temperatures at or below 0°C. When snowmelt exposes the sensor to the air, there is a sudden increase in the diurnal temperature range, with temperatures above 0°C being possible. The date when this occurs is called the snow cessation date. Since the sensors were at 15 cm above the ground, the actual snow-free date at a given location will be later. For this study, treatment average snow cessation dates were determined based on temperature data from all posts. Snow cessation dates have a bearing on when the effective growing season starts at a given location and may influence budburst dates.

Analysis of air temperature data focussed on growing season microclimate conditions at the sites. Two periods when seedlings are considered susceptible to frost damage were defined as the bud flushing (15 May–31 July) and bud set (15 August–30 September) periods. The primary variable of interest was daily minimum 15 cm air temperature at each of the measurement posts described above. Total numbers of frosts ($T_a < 0°C$) and severe frosts ($T_a < -4°C$) were tabulated for the periods of interest on a post by post and treatment average basis. Air temperature growing degree days (GDD) were summed for 1 May to 30 September based on a 5°C daily temperature threshold. For example, if the daily average temperature was 7°C, then the GDD equals 2 for the day. The duration of temperatures below 0°C in minutes (Σt_0) were totalled for periods of interest at each post and averaged over the treatments. Langvall and Orlander (2001) found that frost duration was an important predictor of frost injury to seedlings.

Soil temperature measurements were limited to two replicates per treatment in this study, so a truly representative spatial average cannot be obtained for each treatment; however, soil temperature sensors were placed in areas considered to cover the range of conditions from beneath canopy to canopy gaps. A general comparison of mean soil temperatures was done to see if any treatment differences are suggested. Using daily mean soil temperatures, the soil temperature index (STI) was calculated in the same way as for growing degree days. The STI for a particular day is the total degrees that the daily average soil temperature exceeds a threshold temperature. For example, if a 5°C threshold was set and the daily average temperature was 7°C, then the STI equals 2 for the day. The term STI has been used here to avoid the assumption that the index is related to seedling growth and phenology. The STI integrates such factors as solar irradiance, near-ground air temperature, snow-free season, and soil physical properties. These factors may affect seedling growth and survival; however, no growth effect should be inferred based on the STI alone.

3 RESULTS

3.1 Snow Cessation Dates

Mean cessation dates (2002–2008) for snow cover greater than 15 cm are shown in Table 2 for each treatment. Snow cessation dates for each treatment and year are given in Appendix 1. The data for BEE 15 m^2 cover only the melt seasons of 2006 through 2008. Also, data for the spring of 2005 were excluded from the means at all treatments due to low snowpack conditions where snow cover decreased below 15 cm in mid-winter.

TABLE 2 *Mean, earliest, and latest dates for cessation of snow cover deeper than 15 cm in each treatment unit from 2002 to 2008 (2005 excluded)*

Site	Treatment	Mean date	Earliest date	Latest date
BEE	20 m^2	5 April	24 March	17 April
GLR	20 m^2	7 April	15 March	25 April
UBC	20 m^2	22 March	11 March	11 April
BEE	15 m^2	9 April	30 March	18 April
GLR	15 m^2	2 April	23 March	12 April
GLR	0 m^2	5 April	21 March	19 April

The snow cessation dates were fairly similar for all the treatments, being mostly in the first week of April. An exception is that the mean snow cessation date for the UBC 20 m^2 treatment was 1–2 weeks earlier than at the other treatments. In general, it can be assumed that the ground would be snow-free within 1–2 weeks after these dates, allowing the soil temperatures to begin warming.

3.2 Soil Temperature

Figure 3 summarizes the seasonal (1 May–30 September) totals of STI for each treatment averaged for the period 2002–2008 (except 2006–2008 for BEE 15 m^2). Total STI for each year and treatment are given in Appendix 2. Overall, differences among the treatments were small.

Gavin 0 m^2 had the highest total STI as a result of higher solar loading than the forested treatments. Of note, the Gavin 15 m^2 and BEE 15 m^2 treatments had slightly higher totals of STI than the higher basal area Gavin 20 m^2 and BEE 20 m^2 treatments that were nearby. Although these differences may not be statistically significant, they indicate that the lower basal area treatments allowed more solar radiation to reach the forest floor. The UBC 20 m^2 treatment had the highest STI of the forested treatments. Figure 4 shows a comparison of annual total STI at UBC 20 m^2 with the nearby GLR 0 and 20 m^2 treatment. Before 2005, STI totals at UBC 20 m^2 were similar to those

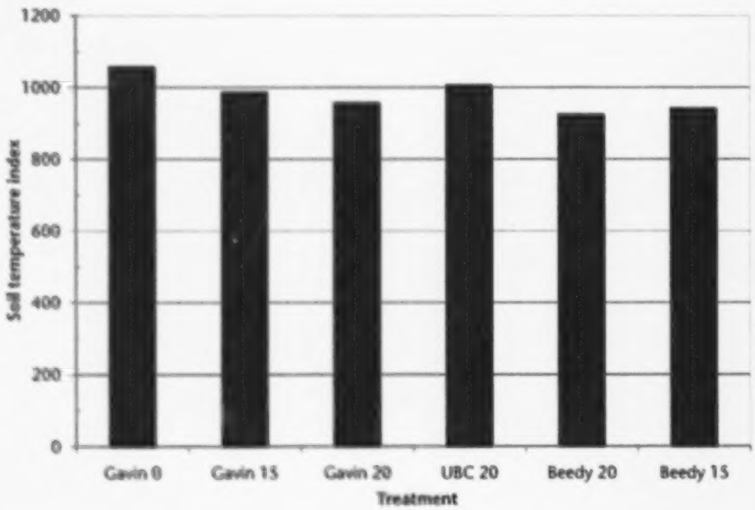


FIGURE 3 *Seasonal (1 May–30 September) mean of soil temperature index for each treatment unit (2002–2008).*

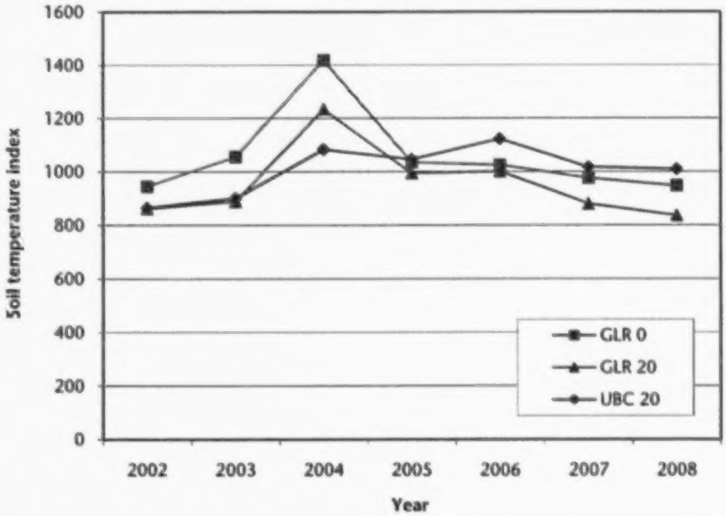


FIGURE 4 *Comparison of annual growing season totals of soil temperature index for the GLR 0 m^2 and 20 m^2 treatments with the UBC 20 m^2 treatment.*

at GLR 20 m^2 and less than those at GLR 0 m^2, while after 2005, UBC 20 m^2 exceeded the other two treatments. This finding might be explained by the declining basal area due to tree fall in the stand, which allowed more solar radiation to penetrate the canopy and reach the forest floor. Increased solar heating of the forest floor leads directly to higher soil temperatures and earlier snow-free dates, which in turn result in a longer period of soil warming.

3.3 Air Temperature

Average frost statistics (2002–2008) for each treatment unit are shown in Table 3 for the bud flushing and bud set periods, respectively. Growing degree days based on 5°C are summarized by treatment and year (Appendix 3). Annual frost statistics (Appendices 4 and 5) and the data on frost duration (Figure 5) are also summarized.

The GLR 0 m^2 treatment was by far the frostiest treatment, with significantly more subfreezing minutes, more days with frost, and lower extreme minimum temperatures. This result is not surprising due to the lack of canopy cover and rolling microtopography which allows cold air to collect in depressions.

Figure 6 shows daily total (2001–2008) frost duration minutes for each treatment unit, covering the bud flush and bud set periods. The duration of subfreezing temperatures was longer during the bud set period in all treatment units, despite this period being one month shorter than the bud flushing period. Accumulation of subfreezing minutes during the bud flushing period was lower due to shorter nights close to the summer solstice, and generally warmer daytime temperatures. Most frosts during this period occurred before 1 June. Much of the total accumulation of subfreezing minutes during a given season can result from only a few nights of frost, which may accumulate 300–500 minutes. These nights typically occur in mid-September to late September when day lengths are shorter. On average, there were two or three fewer frosts during the bud flushing period than the bud set period.

TABLE 3 *Average treatment (2002–2008) frost statistics during the bud flush (15 May–31 July) and the bud set (15 August–30 September) periods. The statistics are based on the spatial mean of 15 cm air temperature taken over all measurement posts. Temperatures are in degrees Celsius and ΣT_0 is the duration of subfreezing temperatures in minutes.*

Site	Treatment	Bud flush				Bud set			
			# of occurrences		Extreme		# of occurrences		Extreme
		ΣT_0	T < 0°C	T < –4°C	Min. temp.	ΣT_0	T < 0°C	T < –4°C	Min. temp.
BEE	20 m^2	686	3	0	–1.4	1322	6	0	–2.4
GLR	20 m^2	892	2	0	–0.9	1155	5	0	–2.4
UBC	20 m^2	670	3	0	–1.6	1346	6	0	–2.8
GLR	15 m^2	914	4	0	–1.8	1727	7	0	–3.1
BEE	15 m^2	416	3	0	–0.6	2358	8	1	–3.6
GLR	0 m^2	1256	8	1	–3.1	2883	13	1	–4.1

Note: Data collection began at the BEE 15 m^2 treatment on 2 June 2005, so means are based on only 2 or 3 years of data for this site.

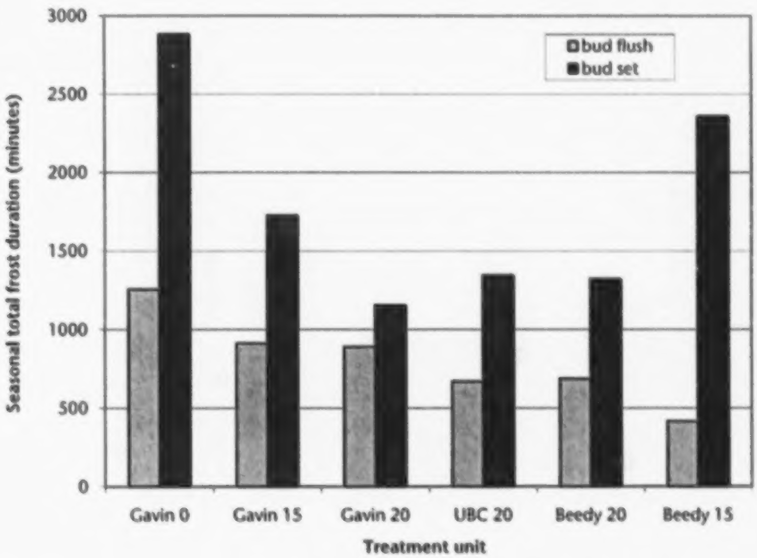


FIGURE 5 *Average seasonal totals of frost duration for the bud flush (15 May–31 July) and bud set (15 August–30 September) periods in each treatment unit (2002–2008).*

The relationship between transect distance (distance along line from tree bole to gap centre) and total accumulated frost duration was tested using data collected from 2001 to 2008. The results for this comparison are show in Table 4. The relationship ranged from very weak at BEE 15 m^2 ($R^2 = 0.02$) to moderate at GLR 15 m^2 where transect distance explained 44% of the variance in frost duration.

During the bud flushing period, the total durations of frost were similar at the paired 15 and 20 m^2 treatments (Table 3); however, there were on average, two more frosts per season at the 15 m^2 treatments. Extreme minimum temperatures were lower at the GLR 15 m^2 treatment unit than the GLR 20 m^2

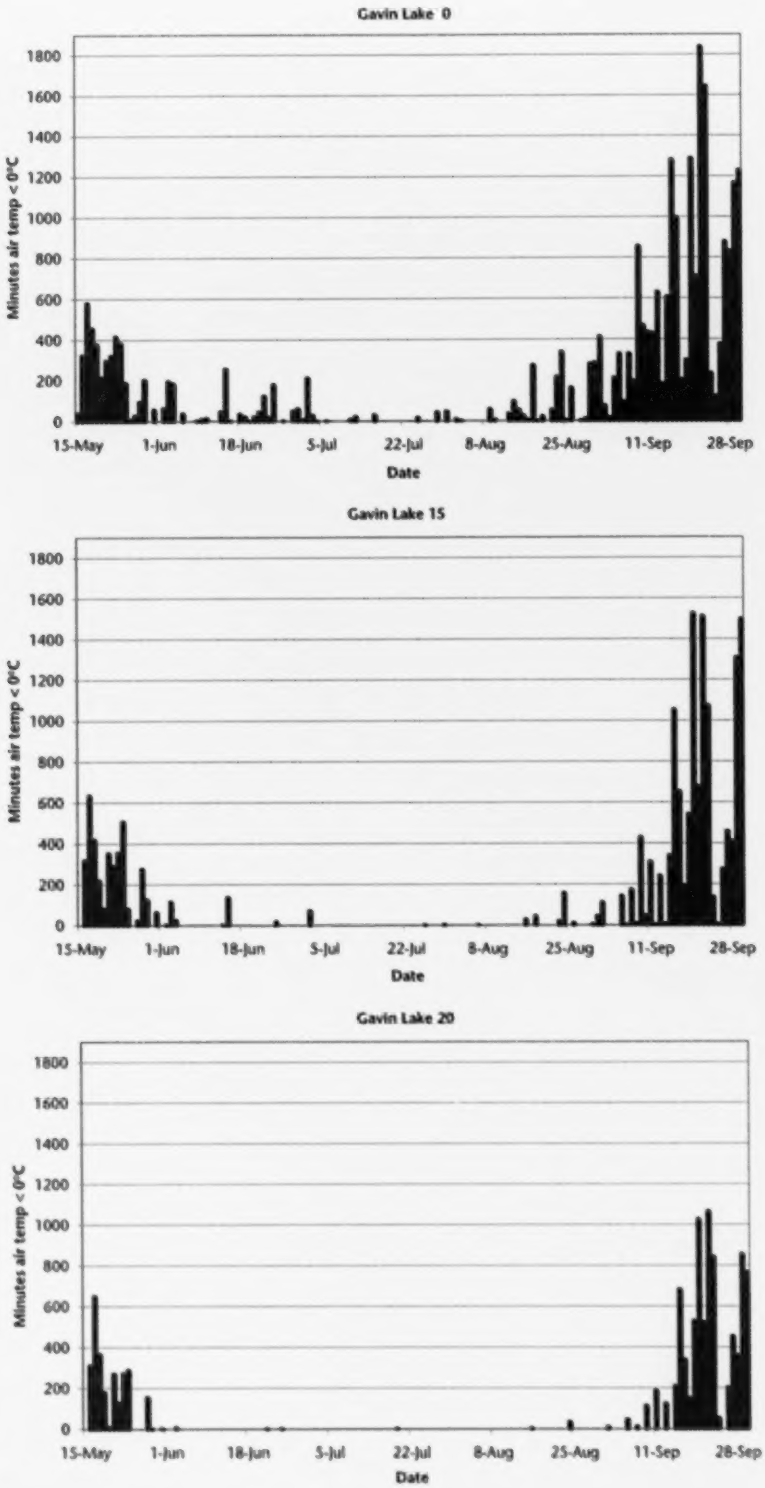
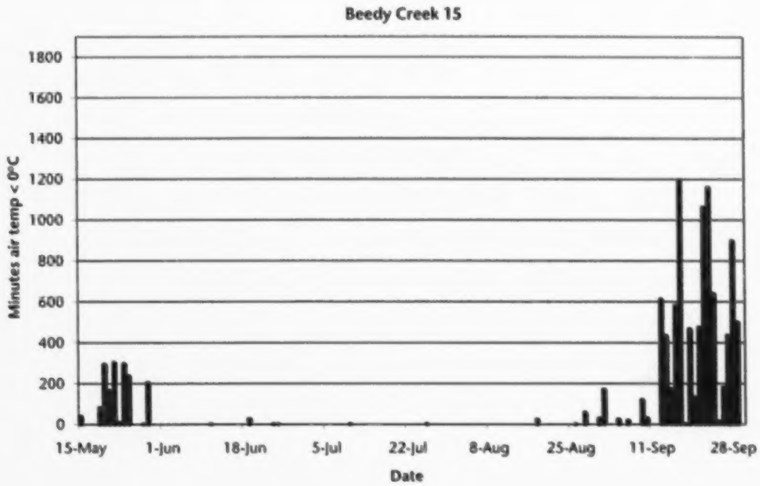
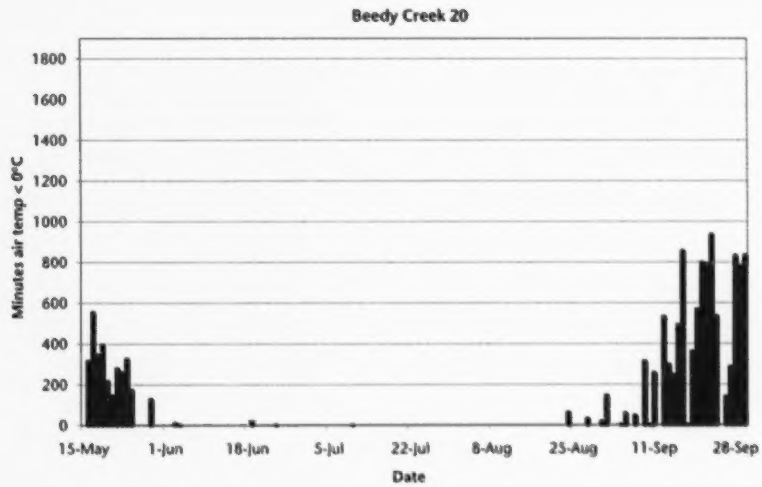


FIGURE 6 *Series of graphs showing total (2001–2008) daily frost duration for each treatment from 15 May to 30 September. Note that data were available only from 2005 to 2008 for the BEE 15 m^2 treatment.*

FIGURE 6 *Continued*





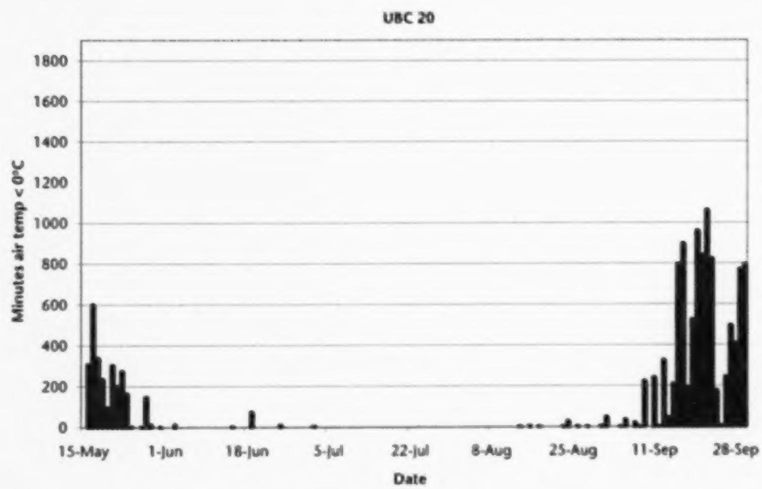


TABLE 4 *Coefficient of determination (R^2) for the relationship between transect distance (distance along a line from tree bole to gap centre) and total accumulated frost duration at each measurement post for 2001 to 2008 (only 2005 to 2008 for BEE 15 m^2).*

Site	Treatment	R^2
BEE	20 m^2	0.31
GLR	20 m^2	0.31
UBC	20 m^2	0.10
BEE	15 m^2	0.02
GLR	15 m^2	0.44

treatment unit. Likewise, from 2006 to 2008 (Appendix 4), the extreme minimum temperatures averaged 0.3°C lower at the BEE 15 m^2 than the BEE 20 m^2 treatment for the bud flushing period.

For the bud set period, there were significantly more subfreezing minutes at the 15 m^2/ha treatments than the nearby 20 m^2/ha treatments. The extreme minimum temperatures were 0.7 to 1.2°C colder and there were more frosts. There was only one severe frost recorded during the eight years of measurement (Appendix 5) at the BEE 20 m^2 and none at GLR 20 m^2 compared with three each at GLR 15 m^2 and BEE 15 m^2 (2005–2008). During the bud setting period, the UBC 20 m^2 treatment had the highest frost duration of the 20 m^2/ha treatments.

Figure 7 compares the daily minimum air temperatures at the GLR 15 and 20 m^2 treatments for the 2007 growing season. This plot is typical of the

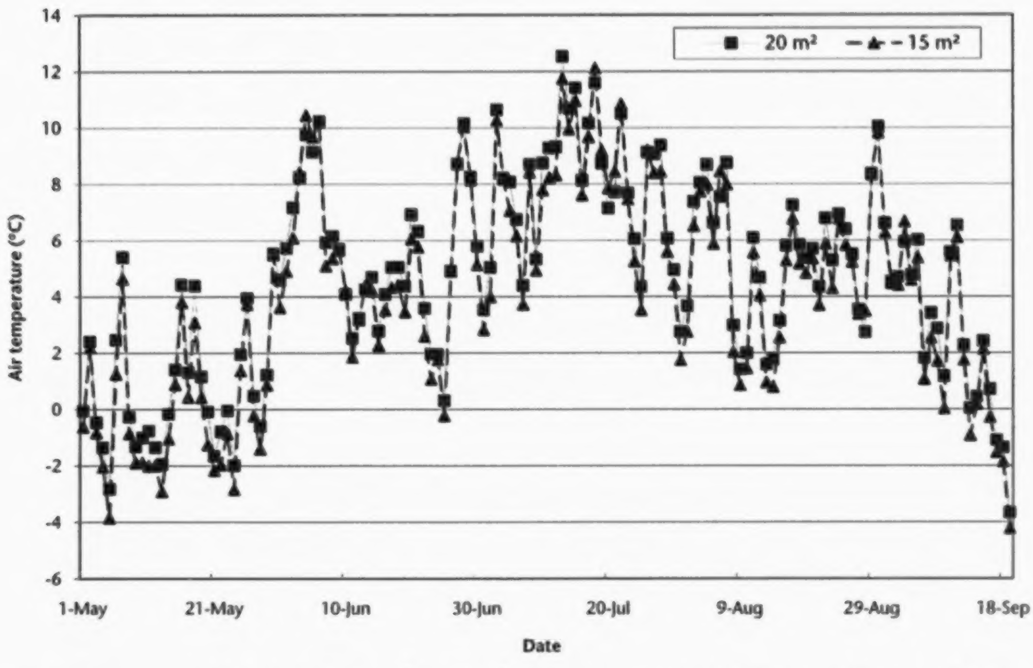


FIGURE 7 *Representative plot for the GLR 15 m^2 and 20 m^2 treatments comparing daily mimimum air temperatures from 1 May to 18 September 2007.*

forested treatments, where most of the frosts occur in May and September. There was one light frost at the GLR 15 m^2 treatment in late June. Minimum temperatures averaged 0.5°C less in the 15 m^2 treatment unit than in the paired 20 m^2 unit, and on some days were as much as 1.3°C colder.

3.4 Canopy Density and Sky View Factor

Two sets of photographs (2001 and 2006) were taken over each air temperature measurement post to determine whether there was a relationship between frost duration and canopy cover. The complete data sets for 2001 and 2006 are given in Appendices 6 and 7, respectively.

Figure 8 shows scatter plots with 1:1 lines comparing the two sets of hemispherical photography for different zenith angle ranges. The plots show that canopy densities in 2001 and 2006 were highly correlated, with points tightly scattered around the 1:1 line. Correlations (R values) decreased as zenith angle increased (larger cone size), taking in more boles and canopy farther from the photo point. At a zenith angle of 90°, R had decreased to 0.63 but the 1:1 line still appears to bisect the data points. A substantial amount of treefall noted in the UBC 20 m^2 treatment might explain why the data points all fall somewhat below the 1:1 line in the scatter plot for a zenith angle of 90°. Overall, however, these plots suggest that there was relatively little change in canopy density.

Treatment average sky view factor based on the 2001 and 2006 fish eye photographs is shown in Figure 9. Average basal area in the UBC 20 m^2 dropped to 12 m^2/ha by 2007 due to treefall in parts of the treatment unit (Table 1). A few trees also fell near the climate station, increasing the sky view factor. In the other two 20 m^2/ha treatments, sky view factors decreased slightly from 2001 to 2006, reflecting growth of the crowns. It was unchanged in the 15 m^2 unit. As would be expected, sky view factors were higher in the 15 m^2 treatments than in the 20 m^2 treatments.

Air temperature sensor locations were set along transects from tree boles to canopy gap centre locations. To test the efficacy of this subjective visual method for determining gap centre, linear regressions were done between transect distance and canopy density in the 10° cone. Figure 10 shows a representative plot of transect distance versus canopy density for the BEE 20 m^2 treatment based on 2001 fish eye photographs. The R^2 value was 0.88, indicating a very strong relationship between canopy density and transect distance. For the other forested treatments, R^2 was moderate to high in each case (0.55–0.84)

The relationship between sky view factor and frost duration was explored to see if sky view factor could be used as a predictor of frost frequency and severity in each treatment unit. The R^2 values for the relationship between sky view factor and frost duration were tabulated for each treatment and year (Table 5). The values varied from year to year and many were so low as to suggest no significant relationship between the variables. An exception to this was the high R^2 value of 0.76 for the GLR 15 m^2 treatment in 2005.

When the data from all the forested treatments were considered together, R^2 values are consistently higher than those for individual treatments (see the line labelled "All sites" in Table 5). These values are, except for those in 2002 and 2008, high enough to infer a meaningful correlation between sky view factor and frost duration.

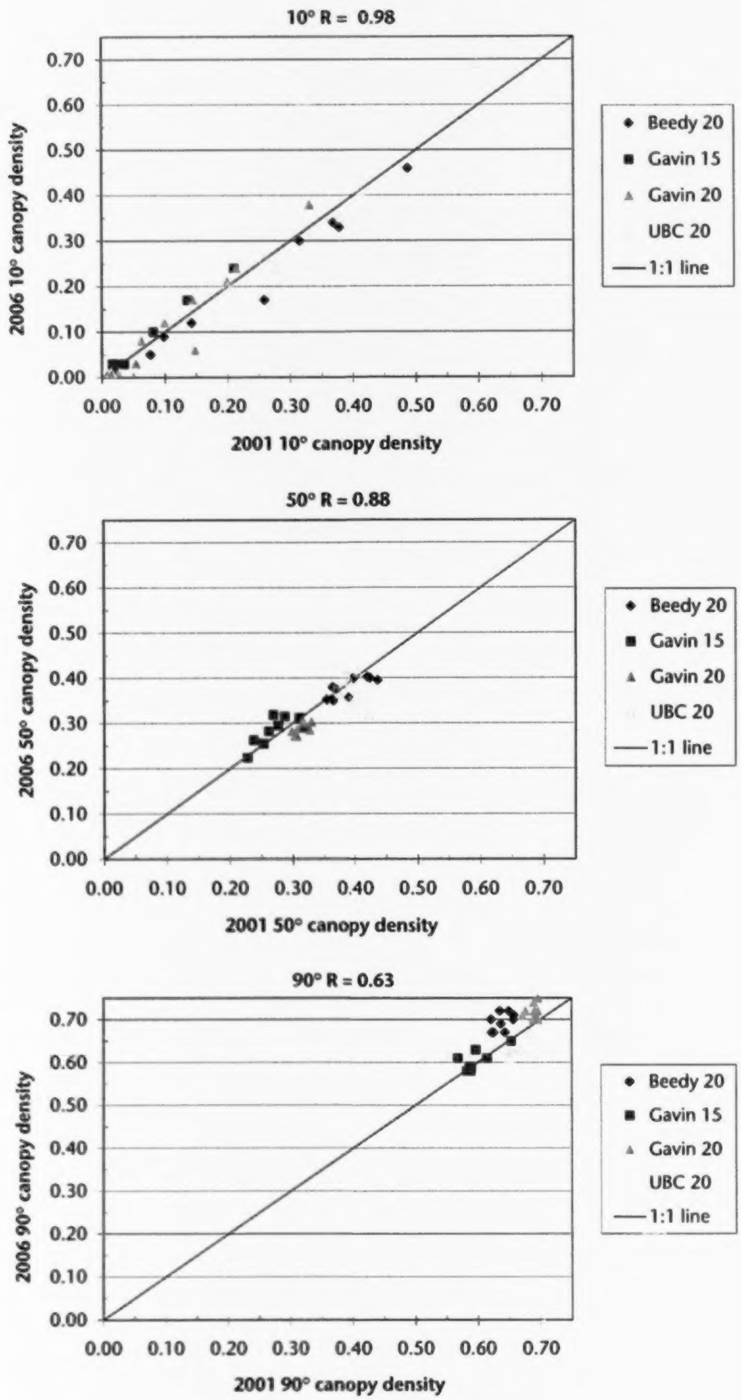


FIGURE 8 *Comparison of canopy densities (determined from fish eye photographs) taken in 2001 and 2006 at three zenith angles: 10°, 50°, and 90°. Note that the zenith angle of 90° means canopy density was determined for the complete hemisphere (0–90°).*

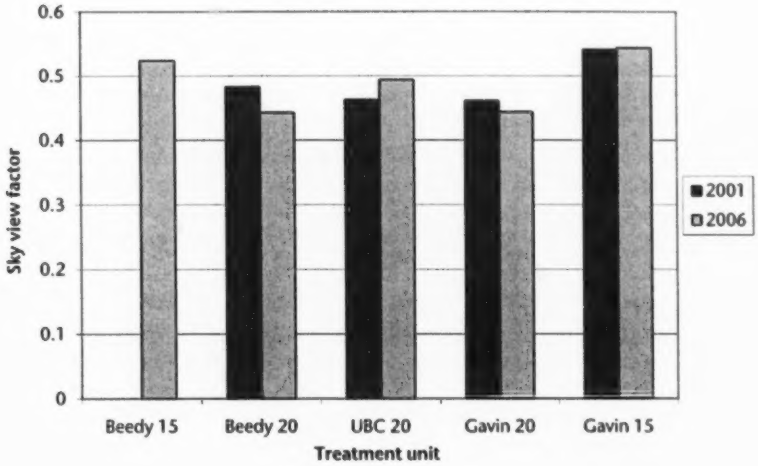


FIGURE 9 *Comparison of average sky view factors between treatment units based on the 2001 and 2006 fish eye photographs. Treatment means are based on pictures taken over the nine measurement posts.*

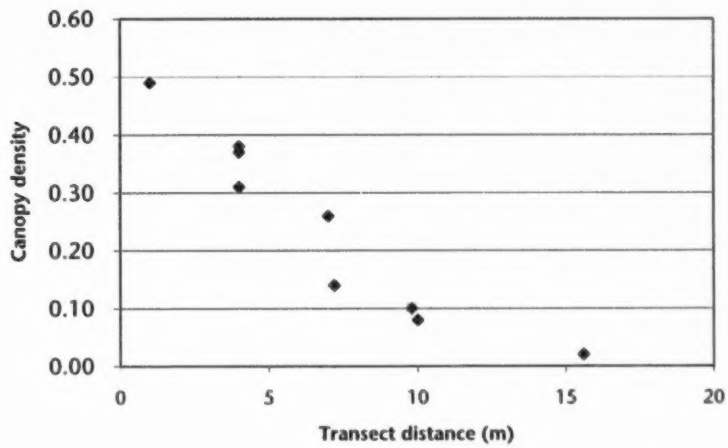


FIGURE 10 *Representative scatter plot of transect distance versus canopy density in the 10° cone. Data are from the 2001 fish eye photographs taken at the BEE 20 m^2 treatment. The R^2 value for these data is 0.88.*

Figure 11 shows a scatter plot of sky view factor versus frost duration for all forested treatments during the 2005 growing season. This growing season has the highest R^2 value (0.57) for the combined forest treatments. Note that in this plot some of the individual treatments show almost no correlation between sky view factor and frost duration. This is apparent in the scatter of data points for the BEE 15, UBC 20, and GLR 20 m^2 treatments. The groupings of data points for each treatment show that sky view factor decreased as basal area decreased from 20 to 15 m^2.

TABLE 5 *Coefficient of determination (R^2) for the relationship between frost duration and sky view factor in each treatment unit and year. The value of R^2 was also determined for all treatments combined (n = 45).*

Site	Treatment	2001	2002	2003	2004	2005	2006	2007	2008
BEE	20 m^2	0.01	0.01	0.02	0.29	0.22	0.33	0.28	0.15
UBC	20 m^2	0.08	0.33	0.02	0.02	0.11	0.19	0.07	0.01
GLR	20 m^2	0.13	0.07	0.08	0.08	0.07	0.00	0.20	0.07
GLR	15 m^2	0.09	0.14	0.07	0.37	0.76	0.47	0.28	0.18
BEE	15 m^2	–	–	–	–	0.01	0.01	0.08	0.05
All sites		**0.49**	**0.20**	**0.39**	**0.37**	**0.57**	**0.41**	**0.34**	**0.10**

Note: Sky view factors derived from the 2001 fish eye photographs were used for the period 2001 to 2003, and sky view factors derived from the 2006 photos were used for the period 2004 to 2008.

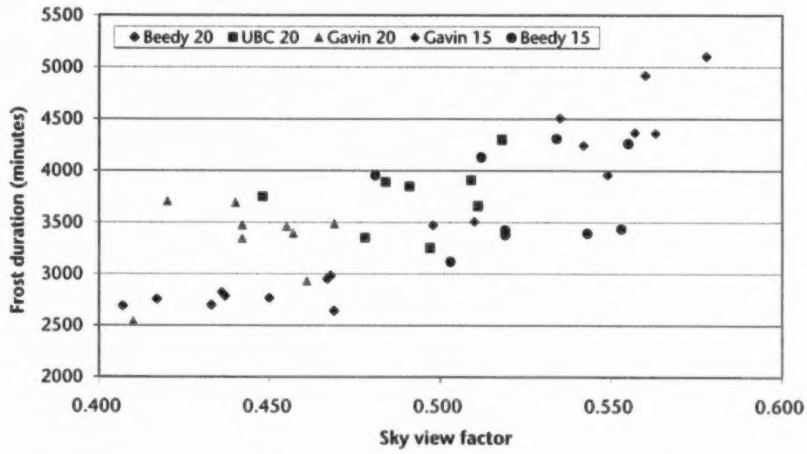


FIGURE 11 *Scatter plot of frost duration versus 2001 sky view factor using data from all forested treatments from 1 June to 6 October 2005. The R^2 value is 0.57 for this data set.*

Growing season frost is a common problem for tree regeneration in boreal and sub-boreal forest areas, especially in clearcuts. Many studies have shown that residual forest cover around small openings (Groot and Carlson 1996; Pritchard and Comeau 2004; Voicu and Comeau 2006) and shelterwoods (Hungerford and Babbit 1987; Blennow 1998; Zasada et al. 1999) reduce frost injury to seedlings. Results from our study show that residual basal area set at 15 m^2/ha and higher effectively reduced frost events in Douglas-fir forests in the Sub-Boreal Spruce biogeoclimatic zone located in the Central Interior of British Columbia. This was confirmed by early results from a natural Douglas-fir regeneration study in the same treatments (Waterhouse and Newsome 2006).

The effect of the residual basal area on growing season frost incidence was clearly demonstrated in the comparison between the clearcut treatment at Gavin Lake (GLR 0 m^2) and the forested treatments (GLR 15 and 20 m^2). During the bud flushing period, GLR 0 m^2 had about 40% greater frost duration than the GLR 15 and 20 m^2 treatments and 67–150% greater frost duration during the bud set period. The GLR 0 m^2 treatment had an average of eight frosts, with one being severe ($T < -4°C$), during the bud flushing period, compared with only two to four frosts, none being severe, at the GLR 15 and 20 m^2 treatments.

Frost injury increases and minimum air temperatures begin to decrease when residual basal area drops below some lower threshold that varies depending on several factors (Langvall and Orlander 2001; Langvall and Lofvenius 2002). These studies in Sweden showed a lower threshold value for residual basal area of about 25 m^2/ha for Scots pine (*Pinus silvestris*) sheltering Norway spruce (*Picea abies*); below this point, frost injury increases as basal area decreases. This threshold value and relationship may differ by species and ecosystem. In our study, the lower extreme minimum temperatures, more frost events in both the bud flush and bud set periods, plus more subfreezing minutes in the bud set period in the 15 m^2/ha treatments compared to the 20 m^2/ha treatments, fit the relationship between minimum air temperature and basal area presented in Langvall and Orlander (2001).

Langvall and Orlander (2001) found that frost duration was a significant factor in determining the amount of frost damage observed on seedlings. There were increased numbers of frosts and longer frost durations in the 15 m^2/ha treatments than the nearby 20 m^2/ha treatments. This was especially true for the bud set period, where for example, GLR 15 m^2 had approximately 50% greater duration of frost than GLR 20 m^2. The differences in frost duration during the bud flushing period between GLR 15 and 20 m^2 were small; however, GLR 15 m^2 averaged two more frosts and extreme minimum air temperatures averaged 0.9°C lower than at Gavin 20 m^2.

Hemispherical photography proved to be a useful tool for quantifying the effects of canopy cover on frost duration in the shelterwood treatments. The data showed that there was little significant change in canopy density from 2001 to 2006. Sky view factor was shown to have a significant positive correlation with frost duration when data from all the forested treatments were considered as a whole (see Figure 11), but a weak to non-existent relationship when individual treatment units were considered. The reason for this result is

that for a given treatment, the measurement points covered a relatively small range of sky view factors (usually < 0.1). Over such a small range in sky view factors, microsite attributes such as soil organic matter, soil type, and microtopography are probably more important than sky view factors as determinants of difference in frost duration among the measurement posts. These findings are consistent with what others have reported in the literature.

The data of Groot and Carlson (1996) and Blennow (1998) showed that minimum air temperatures were highly correlated with sky view factor. Their data sets spanned a much larger range of sky view factors (0–1) than the data presented in this study (about 0.4–0.6). When Blennow (1998) combined topography with sky view factor, her model explained 73% of the variance in minimum air temperatures However, since sky view factor is defined in terms of radiative exchange, it should be even more strongly related to ground and leaf surface temperatures than to minimum air temperatures. It has been demonstrated that plant (leaves, buds, and stems) surface temperatures can fall below air temperatures due to the net loss of longwave radiation to the night sky (Jordan and Smith 1995).

As noted, many site attributes affect the strength of the relationship between sky view factor and frost duration. For example, soil moisture was found to affect the magnitude of the shelterwood effect (Langvall and Lofvenius 2002). When the soil surface was dry, the minimum air temperature was 3.2°C higher in a shelterwood as compared to a nearby clearcut, but only 1.7°C higher under moist conditions. Blennow (1998) showed that local topography, slope configuration, and soil surface types were important determinants of minimum air temperatures. Zasada et al. (1999) also showed that topographic position affected the incidence of frost damage to young deciduous trees in northern Wisconsin. The foregoing discussion suggests that shelterwood density is only one factor that forest managers must consider when making silvicultural prescriptions.

Radiative heat loss (longwave) and convection of cold air, either on a local scale or due to larger scale synoptic processes can lead to frost. These mechanisms have been discussed by Stathers (1989) in some detail. The relative importance of these processes for a given location and time will contribute to determining how factors like sky view factor and local topography influence minimum air temperatures. For example, on flat ground, under clear and calm conditions, radiative processes will dominate over convective processes. In this case, sky view factor may explain a large portion of the variance in minimum air temperatures. In another location, there may be significant local advection of cold air down a slope, which can collect on topographic features such as benches and depressions. In this situation, local topography may take on a greater relative importance and the influence of sky view factor will be less.

During this study there were very few frosts on forested treatments between about 1 June and 25 August (Figure 6). This was especially true of the 20 m^2/ha treatments. The effect of decreasing basal area below 15 m^2/ha is evident, in that there was a significant number of frosts throughout the summer at Gavin 0 m^2 during the June and mid-August periods. The frost statistics quoted in the paper were based on treatment averages. In the case of the Gavin 0 m^2 treatment, there was significantly more frost in the depression and average slope microsites than is indicated by the treatment means. Based on data collected in this study, it can be anticipated that decreasing basal area further below 15 m^2/ha would lead to increasing duration and severity of frosts.

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APPENDIX 1 Dates of cessation of snow cover deeper than 15 cm in each treatment unit (2002–2008)

Site	Treatment	2002	2003	2004	2005	2006	2007	2008	Mean
BEE	20 m^2	12 Apr	ns	25 Mar	5 Feb	24 Mar[a]	8 Apr	17 Apr	5 Apr
GLR	20 m^2	19 Apr	15 Mar	31 Mar	5 Feb	31 Mar	13 Apr	25 Apr	7 Apr
UBC	20 m^2	11 Apr	ns	22 Mar	23 Jan	11 Mar[b]	14 Mar	–	22 Mar
GLR	15 m^2	11 Apr	ns	28 Mar	23 Jan	23 Mar	27 Mar	12 Apr	2 Apr
BEE	15 m^2	–	–	–	–	30 Mar	10 Apr	18 Apr	9 Apr
GLR	0 m^2	19 Apr	21 Mar	3 Apr	25 Jan	24 Mar	13 Apr	12 Apr	5 Apr

ns = no snow cover > 15 cm.
a Snow cover did not exceed 15 cm at two posts.
b Snow cover did not exceed 15 cm at three posts.

APPENDIX 2 Seasonal (1 May–30 September) totals of soil temperature index (STI) for each treatment unit and year (2001–2008). The STI values are based on a 5°C daily mean temperature threshold. Exceptions to the data collection periods are footnoted.

Site	Treatment	2001	2002	2003	2004	2005	2006	2007	2008	Mean
GLR	0 m^2	758	945	1056	1418	1035	1025	976	947	1057
GLR	15 m^2	779	1040	1468	1065	1032	1044	954	919	987
GLR	20 m^2	673	863	889	1234	994	1001	880	836	957
UBC	20 m^2	685	865	901	1083	1046	1123	1017	1009	1006
BEE	20 m^2	693	885	885	1027	951	951	893	882	925
BEE	15 m^2	–	–	–	–	843	992	932	899	941

Highlighted data used in computation of means.

Notes:

Data collection period

Start: 26–28 June 2001 all sites except 2 June 2005 at BEE 15 m^2

End: 29 September 2008 all sites

Missing data

GLR 0 m^2 – 30 July to 30 September 2002; estimated STI by linear regression with Gavin 20

BEE 20 m^2 – 19 July 2004

UBC 20 m^2 – 1–16 May 2008

Bad data

Gavin 15 m^2 – for period 2002–2004 due to failing soil temperature sensors

APPENDIX 3 Seasonal (1 May–30 September) totals of air temperature growing degree days (GDD) for each treatment unit and year (2001–2008). The GDD values are based on a 5°C daily mean temperature threshold. Exceptions to the data collection periods are footnoted.

Site	Treatment	2001	2002	2003	2004	2005	2006	2007	2008	Mean
GLR	0 m^2	728	1010	1150	1107	981	1147	1015	967	1054
GLR	15 m^2	734	990	1106	1095	975	1124	940	926	1022
GLR	20 m^2	723	994	1123	1112	989	1137	980	946	1040
UBC	20 m^2	707	1019	1161	1100	1019	1223	1031	963	1074
BEE	20 m^2	742	1043	1126	1118	1036	1189	1030	997	1077
BEE	15 m^2	–	–	–	–	749	1107	949	896	984

Highlighted data used in computation of means.

Notes:

Data collection period

Start: 26–28 June 2001 all sites except 2 June 2005 at BEE 15 m^2

End: 29 September 2008 all sites

Missing data

GLR 0 m^2 – 30 July to 30 September 2002; estimated STI by linear regression with Gavin 20

BEE 20 m^2 – 19 July 2004

UBC 20 m^2 – 1–16 May 2008

APPENDIX 4 Summary of frost statistics for 15 cm air temperature in each treatment unit during the bud flush season (15 May–31 July) from 2001 to 2008

		BEE 20 m²	GLR 20 m²	UBC 20 m²	GLR 15 m²	BEE 15 m²	GLR 0 m²
2001	min. < 0°C	0	0	0	0	-	23
	days < 0°C	0	0	0	0	-	0
	days < –4°C	0	0	0	0	-	0
	min. temp. °C	2.4	4.0	3.6	3.4	-	1.0
2002	min. < 0°C	1030	1400	1334	1769	-	2597
	days < 0°C	4	5	6	8	-	13
	days < –4°C	0	0	0	0	-	2
	min. temp. °C	–2.6	–2.3	–2.6	–3.4	-	–5.2
2003	min. < 0°C	2290	3726	2085	2432	-	3031
	days < 0°C	6	5	5	8	-	10
	days < –4°C	0	1	2	2	-	4
	min. temp. °C	–3.2	–4.0	–4.6	–4.9	-	–7.2
2004	min. < 0°C	259	266	284	604	-	836
	days < 0°C	1	1	1	4	-	8
	days < –4°C	0	0	0	0	-	0
	min. temp. °C	–1.6	–1.7	–2.3	–2.6	-	–3.7
2005	min. < 0°C	44	1	37	207	0	557
	days < 0°C	1	0	1	3	0	4
	days < –4°C	0	0	0	0	0	0
	min. temp. °C	–0.2	0.2	–0.4	–1.0	0.3	–1.8
2006	min. < 0°C	0	0	0	0	40	405
	days < 0°C	0	0	0	0	1	4
	days < –4°C	0	0	0	0	0	0
	min. temp. °C	0.4	2.0	1.4	1.1	–0.2	–0.5
2007	min. < 0°C	1163	852	879	1389	1599	1235
	days < 0°C	8	6	8	8	9	11
	days < –4°C	0	0	0	0	0	0
	min. temp. °C	–2.3	–2.0	–2.3	–2.8	–2.4	–2.7
2008	min. < 0°C	16	0	73	0	26	133
	days < 0°C	0	0	1	0	1	3
	days < –4°C	0	0	0	0	0	0
	min. temp. °C	0.0	1.5	–0.4	1.0	–0.2	–0.7

APPENDIX 5 Summary of frost statistics for 15 cm air temperature in each treatment unit during the bud set season (15 August–30 September) from 2001 to 2008

		BEE 20 m^2	GLR 20 m^2	UBC 20 m^2	GLR 15 m^2	BEE 15 m^2	GLR 0 m^2
2001	min. < 0°C	926	493	724	1346	–	2791
	days < 0°C	5	5	6	7	–	11
	days < –4°C	0	0	0	0	–	0
	min. temp. °C	–1.7	–1.4	–1.4	–1.9	–	–3.9
2002	min. < 0°C	807	1008	1112	1360	–	–
	days < 0°C	4	4	4	5	–	–
	days < –4°C	0	0	0	0	–	–
	min. temp. °C	–1.9	–1.9	–2.1	–2.1	–	0.0
2003	min. < 0°C	629	630	740	1404	–	2959
	days < 0°C	7	5	5	8	–	17
	days < –4°C	0	0	0	0	–	0
	min. temp. °C	–1.4	–1.2	–1.1	–1.6	–	–3.0
2004	min. < 0°C	828	1006	955	1419	–	1723
	days < 0°C	3	4	4	4	–	6
	days < –4°C	0	0	0	0	–	2
	min. temp. °C	–1.6	–1.7	–1.7	–2.6	–	–4.4
2005	min. < 0°C	2173	2354	2733	3291	3022	4992
	days < 0°C	8	9	11	11	9	19
	days < –4°C	0	0	1	1	0	3
	min. temp. °C	–3.3	–2.7	–4.1	–4.1	–3.6	–5.8
2006	min. < 0°C	994	799	976	1163	1175	1920
	days < 0°C	4	4	4	5	5	7
	days < –4°C	1	0	1	1	2	1
	min. temp. °C	–4.0	–3.7	–4.2	–4.4	–4.1	–6.4
2007	min. < 0°C	2375	1606	1990	2439	3119	2747
	days < 0°C	12	5	10	9	11	13
	days < –4°C	0	0	0	1	1	1
	min. temp. °C	–3.3	–3.7	–3.8	–4.2	–4.0	–4.2
2008	min. < 0°C	1449	685	919	1012	2117	2955
	days < 0°C	5	3	5	4	8	16
	days < –4°C	0	0	0	0	0	1
	min. temp. °C	–1.5	–2.0	–2.6	–2.9	–2.8	–4.9

APPENDIX 6 Canopy density based on fish eye photos taken during the 2001 growing season. Angles represent the size of the cone with respect to the zenith (i.e., 90° is a complete hemisphere).

Site	Post	Transect distance (m)	Crown closure fraction									Sky view factor
			10°	20°	30°	40°	50°	60°	70°	80°	90°	
BEE15	1	1.0										
BEE15	2	4.0										
BEE15	3	7.0										
BEE15	4	10.0										
BEE15	5	15.0										
BEE15	6	4.0										
BEE15	7	7.0										
BEE15	8	10.0										
BEE15	9	13.0										
Site means												
BEE20	1	1.0	0.49	0.36	0.39	0.42	0.45	0.46	0.51	0.56	0.64	0.472
BEE20	2	4.0	0.37	0.34	0.41	0.42	0.44	0.45	0.51	0.58	0.65	0.467
BEE20	3	7.2	0.14	0.34	0.40	0.44	0.45	0.46	0.52	0.58	0.66	0.459
BEE20	4	4.0	0.38	0.37	0.36	0.36	0.40	0.42	0.48	0.54	0.62	0.501
BEE20	5	7.0	0.26	0.34	0.37	0.36	0.38	0.41	0.48	0.55	0.63	0.500
BEE20	6	10.0	0.08	0.28	0.38	0.39	0.40	0.44	0.50	0.57	0.64	0.481
BEE20	7	15.6	0.02	0.15	0.29	0.35	0.39	0.43	0.49	0.56	0.64	0.492
BEE20	8	4.0	0.31	0.32	0.36	0.40	0.43	0.45	0.52	0.58	0.66	0.467
BEE20	9	9.8	0.10	0.25	0.33	0.37	0.38	0.41	0.47	0.54	0.62	0.508
Site means			**0.24**	**0.31**	**0.37**	**0.39**	**0.41**	**0.44**	**0.50**	**0.56**	**0.64**	**0.483**
UBC20	1	1.0	0.60	0.42	0.38	0.40	0.45	0.48	0.53	0.61	0.69	0.442
UBC20	2	2.5	0.41	0.44	0.37	0.39	0.43	0.47	0.51	0.58	0.67	0.460
UBC20	3	5.0	0.26	0.46	0.39	0.39	0.44	0.48	0.53	0.60	0.68	0.446
UBC20	4	2.5	0.38	0.33	0.32	0.37	0.41	0.43	0.48	0.56	0.65	0.489
UBC20	5	4.0	0.20	0.30	0.33	0.38	0.42	0.44	0.50	0.57	0.66	0.476
UBC20	6	7.0	0.01	0.21	0.34	0.37	0.41	0.43	0.48	0.56	0.65	0.489
UBC20	7	10.6	0.01	0.17	0.32	0.38	0.40	0.43	0.48	0.56	0.65	0.489
UBC20	8	4.0	0.28	0.27	0.34	0.39	0.43	0.47	0.53	0.60	0.69	0.449
UBC20	9	7.6	0.02	0.23	0.35	0.42	0.45	0.50	0.56	0.64	0.71	0.423
Site means			**0.24**	**0.31**	**0.35**	**0.39**	**0.43**	**0.46**	**0.51**	**0.59**	**0.67**	**0.463**
GLR20	1	1.0	0.33	0.21	0.29	0.31	0.37	0.45	0.54	0.62	0.70	0.455
GLR20	2	4.0	0.10	0.23	0.30	0.32	0.37	0.46	0.54	0.62	0.70	0.453
GLR20	3	7.0	0.03	0.25	0.28	0.31	0.35	0.45	0.53	0.61	0.69	0.463
GLR20	4	11.2	0.06	0.21	0.25	0.30	0.35	0.44	0.53	0.61	0.69	0.465
GLR20	5	4.0	0.21	0.26	0.25	0.30	0.38	0.45	0.53	0.62	0.69	0.457
GLR20	6	7.7	0.14	0.25	0.24	0.32	0.39	0.45	0.54	0.62	0.70	0.453
GLR20	7	4.4	0.20	0.23	0.31	0.33	0.38	0.45	0.53	0.62	0.69	0.456
GLR20	8	7.7	0.05	0.25	0.31	0.33	0.36	0.44	0.51	0.59	0.67	0.474
GLR20	9	7.6	0.15	0.23	0.24	0.27	0.35	0.43	0.51	0.60	0.68	0.477
Site means			**0.14**	**0.24**	**0.27**	**0.31**	**0.37**	**0.45**	**0.53**	**0.61**	**0.69**	**0.461**
GLR15	1	1.0	0.21	0.18	0.24	0.29	0.36	0.42	0.50	0.58	0.65	0.491
GLR15	2	4.0	0.08	0.17	0.22	0.26	0.33	0.37	0.43	0.51	0.59	0.551
GLR15	3	7.0	0.02	0.17	0.22	0.28	0.34	0.38	0.44	0.51	0.59	0.546
GLR15	4	10.0	0.04	0.15	0.22	0.31	0.37	0.42	0.47	0.54	0.61	0.514
GLR15	5	16.5	0.02	0.06	0.22	0.32	0.36	0.41	0.45	0.51	0.59	0.536
GLR15	6	4.0	0.14	0.11	0.20	0.27	0.34	0.38	0.46	0.52	0.60	0.536
GLR15	7	7.0	0.02	0.09	0.19	0.25	0.31	0.36	0.44	0.51	0.59	0.553
GLR15	8	10.0	0.02	0.04	0.17	0.24	0.28	0.34	0.41	0.49	0.57	0.574
GLR15	9	15.5	0.02	0.09	0.17	0.23	0.29	0.35	0.42	0.50	0.58	0.565
Site means			**0.06**	**0.12**	**0.21**	**0.27**	**0.33**	**0.38**	**0.45**	**0.52**	**0.60**	**0.541**

APPENDIX 7 Canopy density based on fish eye photos taken during the 2006 growing season. Angles represent the size of the cone with respect to the zenith (i.e., 90° is a complete hemisphere).

Site	Post	Transect distance (m)	Crown closure fraction									Sky view factor
			10°	20°	30°	40°	50°	60°	70°	80°	90°	
BEE15	1	1.0	0.54	0.27	0.21	0.25	0.32	0.38	0.46	0.55	0.64	0.519
BEE15	2	4.0	0.11	0.21	0.18	0.24	0.32	0.38	0.46	0.56	0.64	0.519
BEE15	3	7.0	0.13	0.16	0.17	0.22	0.29	0.36	0.43	0.53	0.63	0.543
BEE15	4	10.0	0.01	0.09	0.15	0.20	0.27	0.35	0.43	0.52	0.62	0.553
BEE15	5	15.0	0.02	0.03	0.14	0.20	0.26	0.34	0.43	0.53	0.62	0.555
BEE15	6	4.0	0.29	0.24	0.22	0.25	0.31	0.38	0.48	0.58	0.66	0.503
BEE15	7	7.0	0.04	0.18	0.21	0.24	0.31	0.38	0.47	0.57	0.65	0.512
BEE15	8	10.0	0.02	0.14	0.22	0.28	0.34	0.41	0.51	0.60	0.68	0.481
BEE15	9	13.0	0.01	0.11	0.23	0.28	0.30	0.36	0.44	0.54	0.63	0.534
Site means			**0.13**	**0.16**	**0.19**	**0.24**	**0.30**	**0.37**	**0.46**	**0.55**	**0.64**	**0.524**
BEE20	1	1.0	0.46	0.33	0.36	0.40	0.45	0.50	0.59	0.66	0.72	0.407
BEE20	2	4.0	0.34	0.31	0.38	0.40	0.43	0.48	0.57	0.65	0.72	0.417
BEE20	3	7.2	0.12	0.30	0.34	0.39	0.42	0.47	0.55	0.63	0.71	0.433
BEE20	4	4.0	0.33	0.35	0.36	0.38	0.43	0.47	0.55	0.63	0.70	0.437
BEE20	5	7.0	0.17	0.28	0.34	0.35	0.39	0.43	0.52	0.59	0.67	0.469
BEE20	6	10.0	0.05	0.24	0.32	0.36	0.39	0.43	0.52	0.60	0.67	0.468
BEE20	7	15.6	0.01	0.13	0.28	0.35	0.40	0.45	0.54	0.62	0.69	0.450
BEE20	8	4.0	0.30	0.31	0.36	0.40	0.43	0.47	0.55	0.62	0.70	0.436
BEE20	9	9.8	0.09	0.26	0.34	0.37	0.39	0.43	0.52	0.59	0.67	0.467
Site means			**0.21**	**0.28**	**0.34**	**0.38**	**0.41**	**0.46**	**0.55**	**0.62**	**0.69**	**0.443**
UBC20	1	1.0	0.69	0.41	0.41	0.41	0.43	0.45	0.48	0.52	0.62	0.497
UBC20	2	2.5	0.41	0.42	0.38	0.39	0.43	0.46	0.49	0.54	0.63	0.484
UBC20	3	5.0	0.26	0.47	0.43	0.42	0.46	0.50	0.53	0.59	0.67	0.448
UBC20	4	2.5	0.35	0.32	0.34	0.37	0.43	0.45	0.49	0.54	0.63	0.491
UBC20	5	4.0	0.20	0.29	0.33	0.36	0.40	0.43	0.46	0.52	0.62	0.511
UBC20	6	7.0	0.01	0.22	0.33	0.37	0.39	0.42	0.45	0.52	0.61	0.518
UBC20	7	10.6	0.01	0.18	0.32	0.39	0.40	0.42	0.46	0.53	0.62	0.509
UBC20	8	4.0	0.24	0.27	0.31	0.35	0.40	0.46	0.51	0.57	0.65	0.478
UBC20	9	7.6	0.01	0.18	0.26	0.32	0.36	0.42	0.48	0.54	0.63	0.509
Site means			**0.24**	**0.31**	**0.35**	**0.38**	**0.41**	**0.45**	**0.48**	**0.54**	**0.63**	**0.494**
GLR20	1	1.0	0.38	0.19	0.29	0.31	0.39	0.49	0.59	0.68	0.75	0.410
GLR20	2	4.0	0.12	0.17	0.28	0.29	0.35	0.46	0.55	0.65	0.72	0.442
GLR20	3	7.0	0.01	0.21	0.28	0.30	0.36	0.48	0.58	0.67	0.74	0.420
GLR20	4	11.2	0.08	0.18	0.24	0.27	0.32	0.42	0.52	0.62	0.70	0.469
GLR20	5	4.0	0.24	0.25	0.22	0.27	0.35	0.44	0.53	0.63	0.71	0.457
GLR20	6	7.7	0.17	0.24	0.22	0.28	0.35	0.43	0.53	0.63	0.70	0.461
GLR20	7	4.4	0.21	0.21	0.27	0.30	0.37	0.46	0.55	0.64	0.72	0.440
GLR20	8	7.7	0.03	0.21	0.27	0.30	0.36	0.44	0.53	0.63	0.71	0.455
GLR20	9	7.6	0.06	0.21	0.25	0.29	0.36	0.45	0.55	0.65	0.72	0.442
Site means			**0.14**	**0.21**	**0.26**	**0.29**	**0.36**	**0.45**	**0.55**	**0.64**	**0.72**	**0.444**
GLR15	1	1.0	0.24	0.21	0.26	0.32	0.38	0.41	0.48	0.56	0.65	0.498
GLR15	2	4.0	0.10	0.21	0.25	0.28	0.33	0.35	0.41	0.50	0.59	0.557
GLR15	3	7.0	0.03	0.20	0.25	0.30	0.33	0.35	0.41	0.49	0.58	0.560
GLR15	4	10.0	0.03	0.17	0.24	0.31	0.36	0.39	0.44	0.52	0.61	0.535
GLR15	5	16.5	0.02	0.06	0.20	0.29	0.33	0.38	0.43	0.50	0.59	0.549
GLR15	6	4.0	0.17	0.14	0.24	0.32	0.37	0.40	0.48	0.55	0.63	0.510
GLR15	7	7.0	0.03	0.10	0.19	0.26	0.30	0.34	0.42	0.50	0.58	0.563
GLR15	8	10.0	0.02	0.05	0.18	0.26	0.32	0.37	0.44	0.53	0.61	0.542
GLR15	9	15.5	0.01	0.09	0.17	0.22	0.27	0.33	0.40	0.49	0.58	0.578
Site means			**0.07**	**0.14**	**0.22**	**0.28**	**0.33**	**0.37**	**0.43**	**0.52**	**0.60**	**0.544**